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TESTS OF SHEARING MECHANISM OF SAFETY PINS USED IN SAFETY COUPLINGS

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Abstract:
The paper presents an analysis of issues related to improper shearing of safety pins used in overload couplings. Based on FEM computer simulations, it was established that the highest values of destructive stresses occur at the site of the structural narrowing. Experiments regarding the shearing of safety pins were carried out on a specialized test stand. 4 batches of pins of different hardness and 1 batch of reference pins were subjected to strength tests. Based on the conducted tests, it was established that the hardness of the pin material, which defines the form of the separating fracture, has a significant impact on the correct shear process of the pins. The paper also presents technological and design recommendations that should ensure an appropriate form of decohesion of the safety pin.

Key words: couplings, protections, safety

INTRODUCTION

The drive system [1] is a key element of any machine. It consists of a motor and components that mediate the transfer of energy to the working part, such as mechanical gears [2], couplings [3], articulated shafts [4, 5], and other elements. The drive is connected to the working elements of the machine that perform specific functions.

The correct operation of the drive system is crucial to meeting the functional requirements of the machine [6]. Therefore, each drive system has to be protected against the occurrence of transient operating states. Dynamic loads, which can lead to serious damage to critical components of the machine, are particularly dangerous. The protection of the drive system can be carried out both electrically and mechanically.

In mechanical methods of shaft protection, safety couplings [3] play a key role. Their task is to protect the machine components from overloads caused by working machine actuators. However, in practical solutions, a technical problem has been identified: the destruction of the pins in the gripping section, and not in the shearable section provided for this purpose [7, 8]. Figure 1 illustrates the described problem.

Fig. 1 Example of damage to safety pins outside the narrowing zone
Source: [7].

The location of the formation of the immediate pin fracture has a significant impact on the torque value at which the coupling elements disconnect. This problem was observed regardless of the values of the safety pin diameters.

The paper presents the results of numerical and experimental studies aimed at explaining the problem of the formation of fractures in the wrong location.

LITERATURE REVIEW

Safety couplings, also called overload couplings, are divided into two groups depending on the mode of operation [3]. In the first group, the coupling elements are completely disconnected when the torque increases above the boundary value, and in the second, the transferred torque value is limited to a safe value. In the first group of couplings, solutions with shear couplers in the form of a pin or several pins are commonly used. They are sheared off when the overload limit is exceeded. The material and the diameter of the pin is selected by the designer based on the value of the threshold moment at which the shearing should occur. Often, safety couplings do not constitute a separate structure, but combine the properties of several other types of couplings. Regardless of the design of the coupling itself, their undoubted advantage is the simplicity of their design and the related reliability, high resistance to environmental conditions and low production costs. The main disadvantage is that it is only possible to restart the machine after it has been completely stopped and the pins have been replaced. Fig. 2 presents examples of safety coupling design solutions in which safeguards in the form of shear pins were applied.

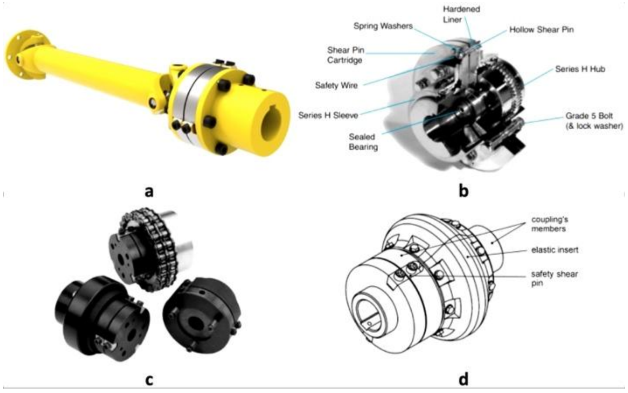


Fig. 2 Examples of safety coupling solutions with shear pins: a – safety couplings integrated with a Cardan shaft [9], b – hollow shear pin coupling [10], c – Sheargard overload couplings from Cross+Morse [11], d – diagram of a RAPTOR-type torsionally flexible coupling integrated with an overload unit

The shear section of the pin typically has a solid or hollow cylindrical cross-section, while the gripping section may be cylindrical or of a different shape, e.g., trapezoidal. Manufacturers specify the accuracy of the shearing force at ±10% of the shearing moment. Despite the undoubted advantages of overload couplings with shear pins, there are situations in which they operate improperly. There is a risk that the coupling will not perform its safety function or that the disconnection of the coupling elements will occur at too low a torque value.

Sankar et al. [12] present issues regarding the operation of a wind turbine in which a safety coupling with 7 shear pins was used in the drive system between the gearbox and the generator. During the operation of this turbine, a fatigue fracture occurred in the area of pin narrowing during operation below the rated power of the turbine. Based on measurements and numerical simulations, it has been established that the decrease in the durability of the pin was caused by increased radial clearance, which led to an increase in the resulting load on the structural node. The authors of the study explain the increase in the load with the occurrence of an additional bending moment, which resulted in a decrease in the load capacity of the pin.

Similar problems regarding a pump drive and a drive system for flocculators in a water filtration plant are described in papers [13, 14]. It has been pointed out that the pins can be fatigue damaged and it has been emphasized that the pins should only work on a shear basis.

Azevedo et al. [15] point out that improper assembly of the coupling (drive unit) also causes the pin to be exposed to bending in addition to shear. The solution may be to redesign the pin to take into account the occurrence of unavoidable assembly errors. Jha et al. [16] draw attention to the problem of non-metallic inclusions in the steel used to produce the shear pins. An excessive number of non-metallic inclusions, located near the structural notch, caused the initiation and propagation of fatigue cracks. The issues of coupling operation and their impact on the durability and properties of drive systems are also analyzed by Kuczaj et al. [17], Filipowicz et al. [18], and Wieczorek et al. [19, 20].

Summarizing the above conclusions resulting from the aforementioned papers, the main irregularities related to the use of shear pins are:

– improper assembly of drive system components,
– failure to meet the assumed dimensional tolerance field in the production process of pins,
– introduction of an additional load into the protection system,
– improper microstructure of the steel used to produce the pins.

RESEARCH METHOD

Based on the performed literature analysis and observed forms of damage to pins, the authors assumed the following possible causes of improper fractures occurring outside the narrowing zone:

- improper design of the shear pin,
- improper installation of the pin enabling the bending of the pin holder,
- improperly selected material properties of the pin for it to perform its securing function.

The authors decided to verify each of these hypotheses by using a dedicated research method. In order to verify the first possible cause, i.e. the improper design of the shear pin, the authors performed numerical tests using the ANSYS Workbench software [21]. Details of the developed numerical model along with computational assumptions have been presented in the following chapter.

The authors verified the remaining 2 hypotheses by conducting tests. The tests involved the use of a test stand (Fig. 3), a ZD-40 testing machine on which a specially designed setting and shearing device has been mounted, ensuring the clean shearing of the pin.

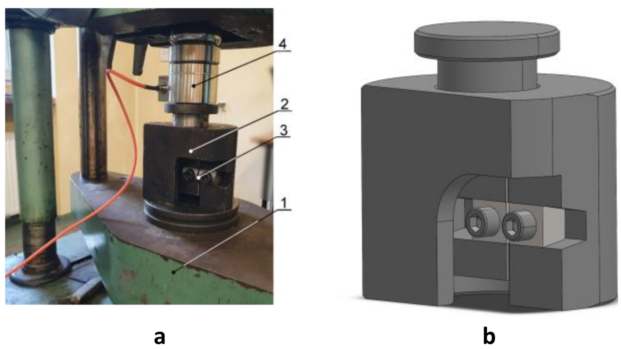
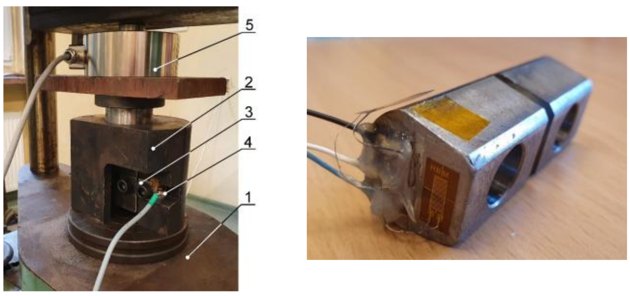


Fig. 3 View of the test stand: a – view of the setting-shearing device with force sensor, b – setting-shearing device; designations: 1 – 400 kN strength testing machine, 2 – setting-shearing device, 3 – tested safety pin, 4 – force sensor

The tested shear pin was mounted on the instrument. The F load applied during the tests was static and was increased at a constant, fixed rate of force build-up. The measurement of the actual value of the F force exerted on the piston of the instrument was carried out using a (4) C6B/500kN sensor by HBM with a dedicated spherical

element [22] and a Quantum X digital measuring and recording system by HBM [23]. The signals from the measurement sensor were recorded using the Catman-Easy software from HBM [24].
In order to confirm the reliability of the obtained results of tests performed as part of the computer simulation of loading, it was necessary to implement a validation process. The validation was carried out by comparing the results of the load simulation in the Ansys program with the existing data obtained on an experimental basis. For this purpose, tests of pin deformation under the impact of a specific load were carried out by means of strain gauge with the use of a test stand (Fig. 4). A ½ strain gauge bridge system was used. A measuring strain gauge was glued to the safety pin; additionally, a compensation strain gauge was attached to the measuring system.



a b

Fig. 4 View of the test stand adapted for strain gauge deformation tests: a – view of the setting-shearing device with force sensor and ½ strain gauge bridge system, b – safety pin; designations:
1 – 400 kN strength testing machine, 2 – special test tool for shearing pins, 3 – tested pin with a glued strain gauge, 4 – ½ strain gauge bridge system, 5 – C2/200 kN force sensor (HBM)

The correct installation of the pin was verified using a high-speed Phantom MIRO LC 120 camera connected to a measurement computer with specialized Phantom Camera Control software [25]. This camera also made it possible to explore the course of the emergence of immediate fractures.
The selection of the material properties of the pin was also verified by means of a shear test and identification of the resulting immediate fracture. For this purpose, an Axia ChemiSEM Scanning Electron Microscope by ThermoFisher Scientific [26] equipped with an EDS X-ray scattering detector was used.
The subject of the research were the pins of the highly torsionally flexible RAPTOR type coupling [27] made of 42CrMo4 steel. Table 1 presents a list of the tested variants, specifying the type of heat treatment and the hardness of the HRC surface.
The chemical composition of Batch I-IV samples was tested using a spectrometer from Spektro [28]. The results of the measurements have been presented in Table 2.

Table 1
List of tested variants

Variant	Material	Heat treatment	Structure	HRC Hardness
Batch I	42CrMo4	Austenitizing (850°C) /Quenching (830°C) /Tempering (520°C)	Sorbit	38±1
Batch II		Austenitizing (850°C) /Quenching (830°C) /Tempering (200°C)	Martensite	55±2
Batch III		Austenitizing (850°C) /Quenching (830°C) /Tempering (520°C)	Sorbit	30±1
Batch IV		Austenitizing (850°C) /Quenching (830°C) /Tempering (300°C)	Martensite	50±2
Batch V (Reference)	-	-	-	10±0.5

Table 2
Chemical composition of ductile iron [mass%]

C	Si	Mn	S	P
0.411 ± 0.012	0.312 ± 0.002	0.743 ± 0.003	0.045 ± 0.004	0.048 ± 0.002
Cr	**Cu**	**Ni**	**Mo**	
1.03 ± 0.01	0.0571 ± 0.0004	0.059 ± 0.002	0.006 ± 0.001	

Figure 5 presents the views and numerical models of the tested safety pins.

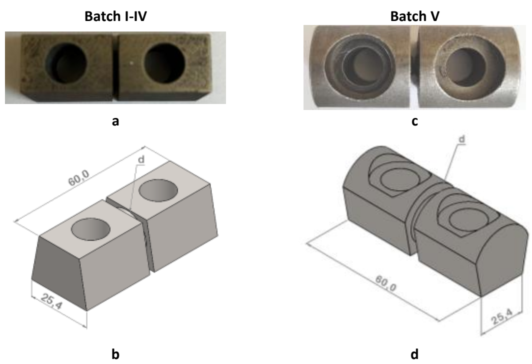
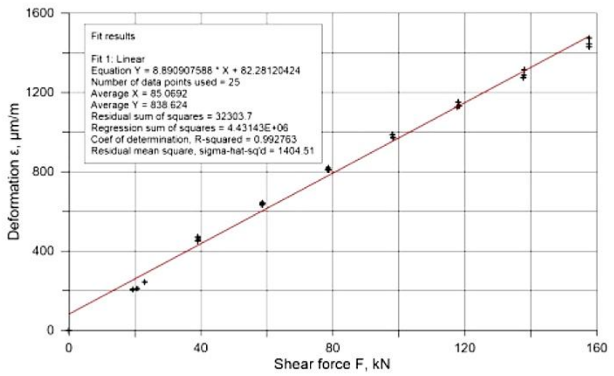


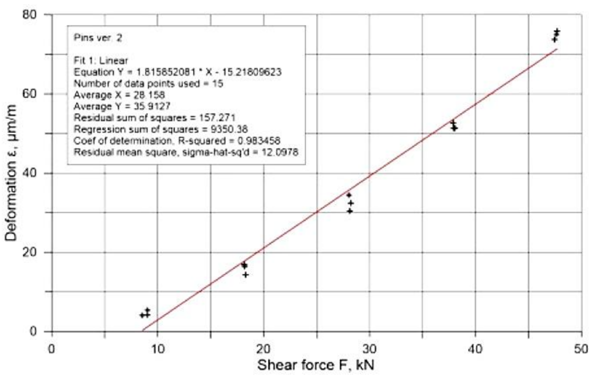
Fig. 5 Tested safety pins:
a – view of Batch I-IV pin, b – Batch I-IV pin model, c – view of Batch V pin, d – Batch V pin model

Numerical Analysis of the Shear Pin Design
In order to verify the correctness of the design of the safety pin, numerical tests of two pin designs were carried out using FEM computer simulation in the Ansys Workbench program. The pin together with setting-shearing

device was modeled, thus reproducing the actual test conditions. After conducting preliminary computer simulations, a tetrahedron finite element was selected. For pins of batches I-IV, 3823 elements with 6817 nodes were assumed, while for pins of batch V - 3618 elements with 6568 nodes. It was assumed as a verification criterion that the correctness of the design will be confirmed when the maximum stresses are located in the pin narrowing zone.
In order to confirm the reliability of the obtained results of tests performed as part of the computer simulation of loading, it was necessary to implement a validation process. The validation was carried out by comparing the results of the load simulation in the Ansys program with the existing data obtained on an experimental basis.
For this purpose, tests of pin deformation under the influence of a specific load were carried out by means of strain gauge with the use of a test stand (Fig. 4). Figures 6a and 6b show the course of the measured pin deformation as a function of the applied load (in the form of shear force) for both pin designs (Batches I-IV and V). As it may be noted, there is a high repeatability of the obtained results from subsequent trials, and the nature of the change in the deformation of the pin as a function of the force is linear.



a

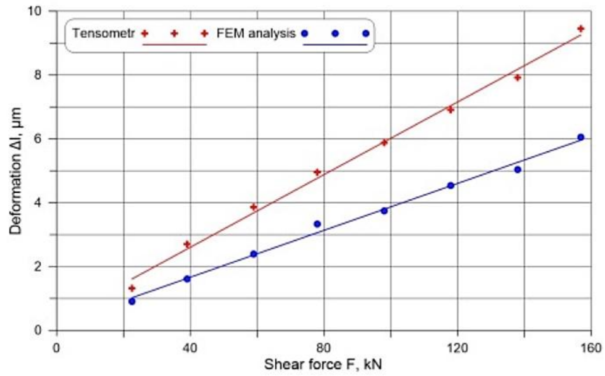


b

Fig. 6 Deformation as a function of the applied load: a – for Batch I-IV pins, b – for Batch V pins

The calculations were validated by comparing the results of the deformation of the pins in the direction of the measured deformation, obtained from the load simulation in the Ansys program, with the results of the deformation from the strain gauge tests. Figures 7a and 7b show a comparison of the obtained results.

When comparing the courses obtained from experimental studies and using computer simulation, it was established that there is a similarity for both forms of pins. The courses can be described using a linear function. In the case of Batch I-IV pins (Fig. 7a), the deformation values at the place of application of the strain gauge, for the results obtained from the computer simulation, are lower in the entire range of the applied load.



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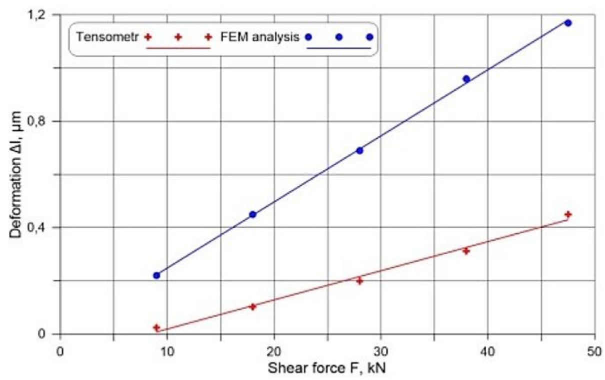

b

Fig. 7 Comparison of the deformation values determined using FEM strain gauge and simulation methods as a function of the applied load: a – for Batch I-IV pins, b – for Batch V pins

The opposite is true in the case of Batch V pins (Fig. 7b), for which the values from the numerical calculations were higher in the entire range of the applied load. The results of tests and simulations confirmed their similarity, both qualitative and quantitative. This may be due to the difference in the shape of the pins of parts I-IV and V, especially at its narrowing zone.
The adopted model for simulation tests under load shows behavior similar to the actual one. On the basis of the validated model, the stress distribution occurring in the pin during shear loading was calculated (Fig. 8).
In the analysis of the above results, it may be noted that stress accumulation occurs in the part in which the correct structural shearing is to occur. In the case of Batch I-IV pins, higher stress values also occur in the gripping part, which is not the case with Batch V pins.

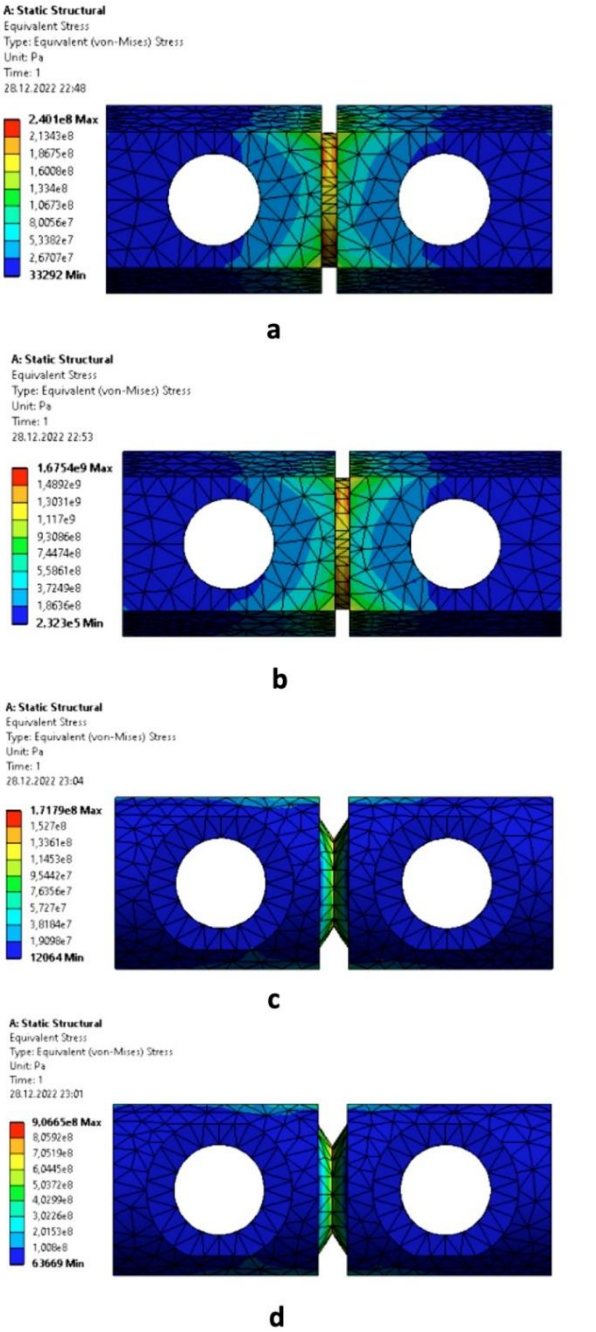

Fig. 8 Stress map of the tested pins: a – determined for Batch I-IV and loads of 22.5 kN, b – determined for Batch I-IV and loads of 157.0 kN, c – determined for Batch V and loads of 9.0 kN, d – determined for Batch V and loads of 47.5 kN

Based on the obtained results of simulation tests, it was established that despite the tension in the gripping part of the Batch I-IV pins, its greatest accumulation occurred in the right place, where it should be sheared, i.e. on the d structural diameter. Therefore, the shape of the pin itself does not have a decisive impact on the process of its improper shearing.

Verification of Correct Assembly of the Safety Pins

Figure 9 shows selected frames from a film made using a high-speed camera documenting the shear process of the pins. Based on the analysis of all the tested pin batches, it was established that the proper method of fixing the pins was ensured in order to prevent the formation of an additional bending moment.

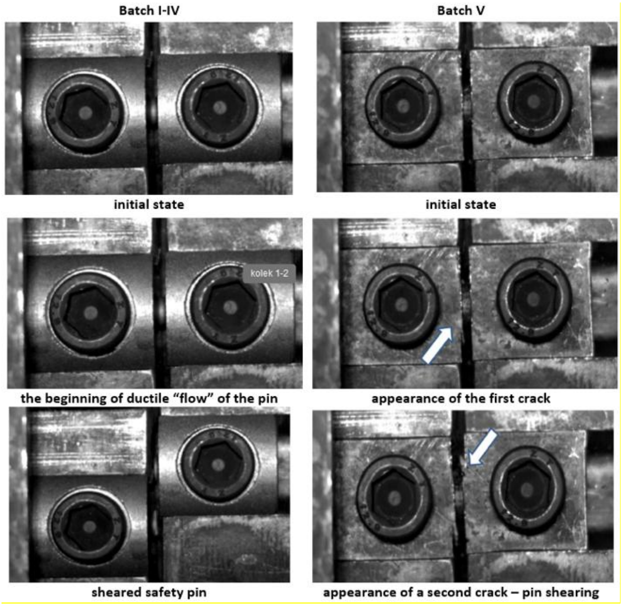

Fig. 9 Stages of the pin shearing process

Results of the Experimental Shear Tests of the Pins

Due to the problem regarding the improper shearing of safety pins used in safety couplings, an attempt was made to experimentally explain the problem. The forms of damage to the tested safety pins are presented in Table 3.

Table 3
Forms of damage to the tested safety pins

Batch No.	Damage view	Damage location
I		In the narrowing zone
II		Outside the narrowing zone
III		In the narrowing zone
IV		Outside the narrowing zone
V		In the narrowing zone

The average values of the FTśr shear force are presented in Figure 10.

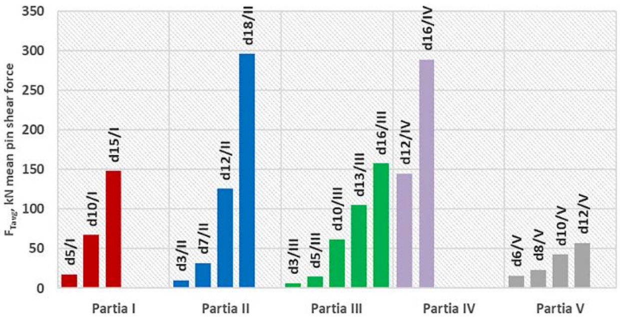

Fig. 10 The mean values of the F_{Tavg} shearing force for all tested pin batches and d diameters in the given pin batch

Based on the conducted pin shear tests, the following was established:

- all tested samples from Batches I and III were sheared in the place designated for this purpose, i.e. in the structural narrowing zone with d diameter,
- the shearing process for Batch II and IV pins, with the exception of the pin with the diameter d = 3 mm, did not proceed correctly: the shearing occurred in the assembly part, and not in the part intended for this purpose, i.e. on the d diameter.
- for the reference batch (V), the fracture was formed in the right place, i.e. in the narrowing of the d structural diameter of the pin; the correct shearing mechanism was observed for all pins from the tested diameter range.
- for the considered pin batches, the location of the damage depended on the hardness range of the pin: for the lower hardness range (30÷38 HRC), the fracture occurred in the designed place, i.e. in the narrowing, while for the higher hardness range (50÷55 HRC), the fracture occurred in the assembly part.

Based on the last observation, the authors decided to carry out identification tests of the resulting fractures.

Fig. 11 shows a sample microphotograph of a Batch IV sample, showing a fracture outside the planned shear zone, along with the surface distribution of elements.

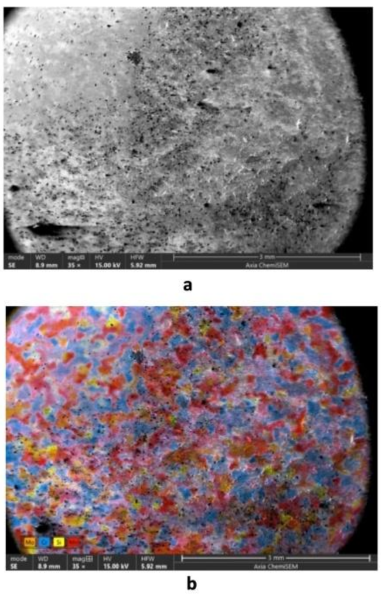

Fig. 11 Fracture of Batch IV sample: a – view of the fracture, b – surface distribution of elements; SEM

The distribution of the analyzed elements (Mo, Si, Mn and Cr) was largely even, which allows to conclude that there was no heterogeneity of chemical composition in the analyzed batch.

Fig. 12 shows a view of fractures of a Batch I pin sample (showing a fracture in the planned shear zone) and a Batch IV sample (showing a fracture outside the planned shear zone). The fracture in Batch I exhibits features of a ductile fracture, while the fracture in Batch IV exhibits features of a brittle fracture.

The change in the form of the fracture should be explained by the greater susceptibility of materials with a martensitic structure (which is typical for hardness above 50 HRC) to brittle cracking, which has been demonstrated in a number of studies [29, 30, 31].

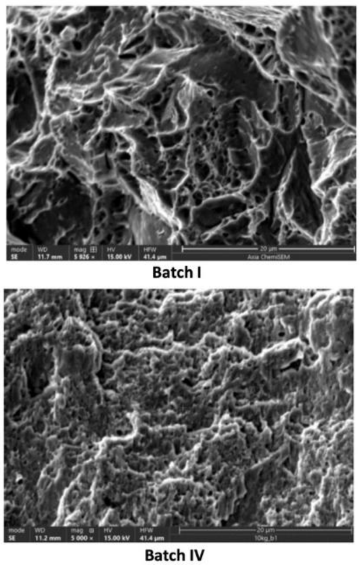

Fig. 12 View of fractures of a Batch I pin sample (left figure) and a Batch IV sample (right figure)

CONCLUSIONS

The process of improper shearing of pins used in safety couplings may cause damage to machines and risk to persons in the vicinity (due to detachment of parts of the damaged pin). Moreover, damage to the pin in the gripping part causes difficulties in its disassembly. Due to the industry-reported issue regarding improper shearing of safety pins used in safety couplings, an attempt was made to experimentally explain the problem.

Based on the conducted shear tests and hardness measurements, FEM numerical strength analyses and analyses of the chemical composition of all batches of pins, it was established that the correct shear process is significantly influenced by the hardness of their material, which implicates the form of the fracture of a given pin. For the considered pin batches, the location of the damage depended on the hardness range of the pin: for the lower hardness range (30÷38 HRC), the fracture occurred in the designed place, i.e. in the narrowing, while for the higher hardness range (50÷55 HRC), the fracture occurred in the assembly part. The fractures of the pins characterized by lower hardness exhibited ductile features, while the fractures of the pins characterized by higher hardness exhibited brittle fracture features.

Based on the conducted tests, the following structural and technological recommendations regarding the manufacturing of safety pins can be formulated:

- martensitic structure of safety pins should be avoided,
- as small a number of safety pins as possible should be used in order to ensure their proper operation,
- the correct moment causing the separation of the protected shaft should be determined by the appropriate d diameter of the safety pin in the area of its narrowing,
- the preferred type of heat treatment is quenching and tempering,
- it is recommended to perform a shear test of a pin dedicated to a given coupling subjected to a fixed heat treatment before the final assembly of the protection; in the event of an incorrect shear mechanism of a pin of a given shape, the heat treatment parameters should be optimized in order to ensure a sorbitic structure and lower hardness.

Acknowledgements

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